A New Divertor System Using Fusible Metal Pebbles*)

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A fusible metal pebble divertor system named the REVOLVER-D2 is newly proposed here, based on the molten tin jet divertor REVOLVER-D and the pebble divertor concepts. In the REVOLVER-D2, solid tin pebble flows are used as the divertor target. Molten tin pools receive the falling tin pebbles to mitigate the impact of the heavy metal shower. All pebbles are melted in the molten tin pool and recycled into the tin pebbles again. The solid tin pebbles are formed inside the vacuum vessel by the shot tower method using silicone oil pools. This concept enables simultaneous achievement of a high heat load tolerance and a high evacuation efficiency, while mitigating the MHD effects. A high heat load can be removed by the pebble flow if the pebble size is large enough and the velocity is fast enough as with the molten tin jet. Although the charge up of pebbles affects the pebble motion due to the Lorentz force and the Coulomb force, the Lorentz force is negligible if the injection velocity is fast enough. For example, center-to-center pebble distance due to the Coulomb force will be ~ 4 mm in the case of the injection velocity of 10 m/s if the molten tin pool is placed 2 m under the point where pebbles enter the ergodic layer.

Keywords: divertor, liquid metal, fusible metal, pebble divertor, conceptual design

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1. Introduction

A high heat load exceeding 20 MW/m^2 is expected for the divertor in typical nuclear fusion reactors. This is larger than the tolerable heat load of the "state-of-the-art" divertor being developed for ITER [1]. To solve this problem, "renewable" divertor concepts such as the liquid metal divertors and/or limiters [2–5], pebble divertors [6–8], etc., have been investigated. A liquid metal divertor named the REVOLVER-D (Reactor oriented Effectively VOLumetric VERtical Divertor) consisting of molten tin shower jets has been proposed for the helical fusion reactor FFHR [9, 10]. Molten tin shower jets on the REVOLVER-D are inserted into the ergodic region of the plasma as a limiter/divertor. Tin is selected as the working fluid because of its low vapor pressure [11], low melting point (~ 230°C), low material cost, low toxicity, no explosive reaction with water, and high nuclear stability (tin has 10 stable isotopes, the largest number of any elements) [12]. The REVOLVER-D is expected to tolerate a high heat load larger than a few tens of MW/m^2. Neutrals generated from the plasma hitting on the surface of the shower jets are easily evacuated through the gaps of the shower. Then, a high evacuation efficiency can be expected. Easy maintenance is also the merit of the REVOVLER-D.

Formation of stable and continuous molten tin shower jets is necessary to prevent the plasma particles from passing through the jets and hitting the vacuum vessel wall. However, continuous molten tin jets can be deformed by the Lorentz force under the existence of the magnetic field and the electric current from the plasma. If the deformation is inhomogeneous, the heat load can be concentrated on a local part of the jets. The electric current should be mitigated. There are several methods to mitigate the electric current, such as the divertor detachment [13–15], use of the droplet flow [16], and so on. However, steady state sustainment of the divertor detachment is difficult in a highly radioactive environment due to the malfunction of measurement instrument by the radiation. In the case of the droplet flow, formation of gaps between droplets is inevitable. Special mechanisms [16] or many showerheads are required to achieve a high shielding rate, resulting in the increase of the engineering design difficulty.

If a high-density solid pebble flow is used instead of the molten tin shower jets or droplet flows, it becomes possible to cut the electric current and to achieve a high shielding rate simultaneously. In the past pebble divertor design, ceramic pebbles and ferromagnetic pebbles have been adopted. However, the exchange of broken pebbles is necessary [6–8]. Here, we propose a new concept of Fusible Metal Pebble Divertor (FMPD) named the REVOLVER-D2, which uses tin pebbles. This concept enables a higher permissible heat load than the divertors using the water-cooled tungsten, the liquid metal jet, or the ceramic pebbles. There is no need of high temperature liquid metal pump. The corruption of pebbles is not a problem on the

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FMPD. In-situ reproduction of the pebbles is possible.

This paper describes the basic concept of the REVOLVER-D2 and the design requirement on the pebble flow. The overall picture of the REVOLVER-D2 is described in Section 2. The average temperature increase of the pebble is evaluated in Section 3. The influence of pebble charge up is discussed in Section 4. These are summarized in Section 5. Parameters used in this paper are listed in the Appendix.

2. Overall Picture of the REVOLVER-D2

A schematic view of the REVOLVER-D2 is shown in Fig. 1. The basic scenario proceeds as follows: 1) tin pebbles are fallen from the nozzle to the ergodic layer and act as a divertor target, 2) all pebbles drop into the molten tin pool and become melted, 3) pebbles are reproduced by the shot tower method using the silicone oil pool, 4) the pebbles are transported to the nozzle and fallen to act as the divertor target again.

During the plasma exposure, a part of the pebbles is melted (in the region (A) in Fig. 1). All tin pebbles are received by the molten tin pool and melted inside the pool (in the region (B)). As will be described in the next section, the temperature of the molten tin pool is expected to be < 1,200 K. This molten tin pool works as a cushion against the drop impact of the pebbles. The thermal energy of the molten tin is utilized for the power generation and the temperature of molten tin is cooled to ~ 600 K by a heat exchanger (in the region (C)). Then the molten tin is transported to the showerhead that is placed above the silicone oil pool of ~ 300 K. The molten tin droplets are issued into the silicone oil and tin pebbles are formed by means of the shot tower method (in the region (D)). Because the vapor pressure of silicon oil at ~ 300 K is as high as ~ 10 Pa, an S-pipe is installed between the molten tin pool and the shower head to prevent the backflow. The pebbles are transported to the nozzle by slopes and a spiral elevator (in the region (E)), and then injected to the plasma again. During the transportation, the pebbles are cooled and desiccated. The degree of vacuum is controlled by the differential pumping.

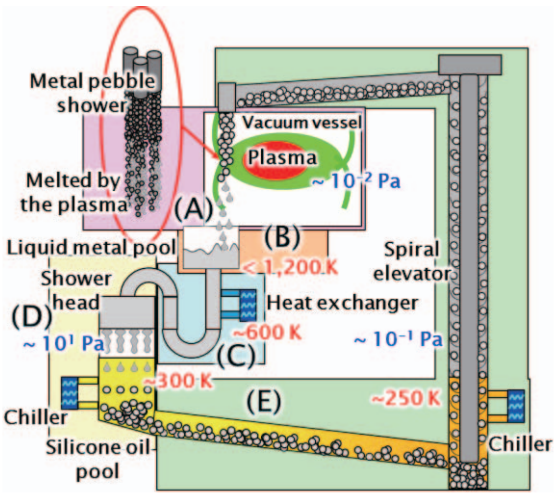

Fig. 1 A schematic view of the REVOLVER-D2.

3. Global and Local Thermal Analyses

3.1 Total mass flow rate

The required total mass flow rate is determined by the acceptable temperature increase. The relation among the divertor heat load, the temperature increase, and the heat of fusion on the all flowing tin is given by:

$$P_{\mathrm{div}} = \Delta T_{\mathrm{all}} C_{\mathrm{Sn}} \rho_{\mathrm{Sn}} Q + \chi_{\mathrm{Sn}} \rho_{\mathrm{Sn}} Q. \tag{1}$$

From this equation, the average temperature increase of all tin flow is given as:

$$\Delta T_{\mathrm{all}} = \frac{P_{\mathrm{div}}}{C_{\mathrm{Sn}} \rho_{\mathrm{Sn}} Q} - \frac{\chi_{\mathrm{Sn}}}{C_{\mathrm{Sn}}}, \tag{2}$$

where $P_{\mathrm{div}} = P_\alpha + P_{\mathrm{aux}} - P_{\mathrm{rad}}$, P_{rad} is assumed to be $(P_\alpha + P_{\mathrm{aux}}) \times 30\%$, and $P_\alpha = P_{\mathrm{fusion}}/5$ (see Appendix for definition of the parameters used in this paper). In the case of the helical fusion reactor FFHR-c1, P_{fusion} and P_{aux} are assumed to be 370 MW and 25 MW, respectively. Then, the power flows into the divertor region is ~ 70 MW. The resultant heat flux on the pebble shower in the FFHR-c1, which depends on the layout of the shower with respect to the plasma, is roughly estimated to be 60 - 100 MW/m^2. If the temperature of tin is suppressed below 1,200 K, the vapor pressure can be kept below the order of 10^{-2} Pa, which is much lower than the expected exhaust pressure of the order of 0.1 - 1 Pa [9]. To achieve this, the temperature increase needs to be suppressed to ~ 900 K. Consequently, the required total mass flow rate of the tin pebble $\rho_{\mathrm{Sn}} Q$ is estimated to be ~ 920 ton/h.

3.2 Average Temperature increase of a tin pebble

Since the plasma mainly hit the outermost layer of the pebble flow, the heat load on each pebble will not be homogeneous. The temperature increase of a single pebble averaged over the pebble volume, $\Delta T_{\mathrm{pebble}}$, can be evaluated by the following equation:

$$\Delta T_{\mathrm{pebble}} = \frac{q(\pi r^2)\Delta t - \chi_{\mathrm{Sn}} \rho_{\mathrm{Sn}} \left(\frac{4}{3}\pi r^3\right)}{C_{\mathrm{Sn}} \rho_{\mathrm{Sn}} \left(\frac{4}{3}\pi r^3\right)}. \tag{3}$$

The final temperature of the single pebble after passing through the ergodic layer depends on the velocity and the initial temperature.

Figure 2 shows the final average temperature of a solid tin pebble and a liquid tin droplet as a function of the injection velocity (the velocity when the pebble enters the ergodic layer). The passing length of the ergodic layer in

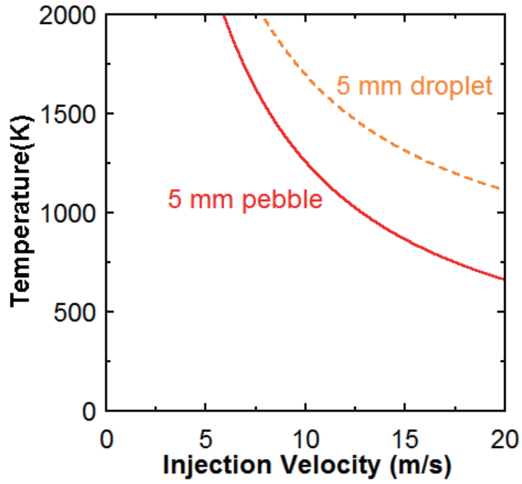

Fig. 2 The relation between the average temperature and the injection velocity for the solid tin pebble (solid line) and liquid tin droplet (broken line).

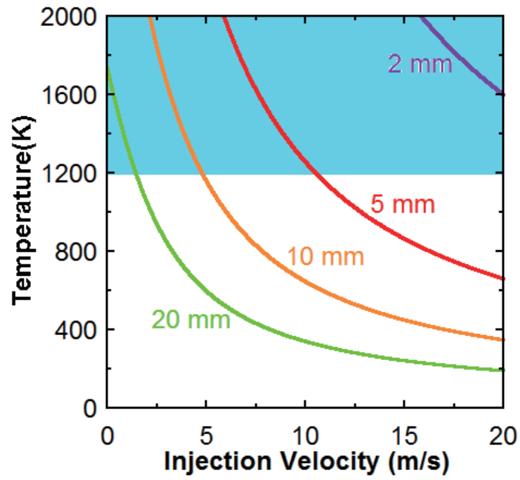

Fig. 3 The dependence of the relation between the average temperature and the injection velocity on the pebble diameter.

the FFHR-c1 is ~ 0.7 m. It is assumed that a constant heat flux of $q = 100\,\mathrm{MW/m^2}$ is applied to the pebble. The final average temperature of the solid pebble averaged over the pebble volume can be lower than that of the liquid droplet at the same injection velocity. This is because the initial temperature is lower and there is a heat absorption by the latent heat in the case of the solid pebble. Therefore, a better heat load toleration property can be obtained in the case of the solid pebble.

Figure 3 shows the dependence of the final temperature of the solid tin pebble on the pebble diameter. The required injection velocity decreases with the increase of the pebble diameter. If the drop distance is set to 5 m, then the injection velocity after free-fall is ~ 10 m/s. In this case, for example, the pebble diameter of > 5 mm is needed to keep the final temperature below 1,200 K.

4. Force Balance on a Tin Pebble

The electric current of the divertor target can be mitigated by using the solid metal pebble flow instead of the continuous liquid metal jet flow. It should be noted, however, that pebbles irradiated by the plasma will be charged up. Then, the Coulomb force and the Lorentz force act on the pebbles and affect the motion of the pebble flow. The total electric charge can be estimated using the model given in Refs. [17, 18]. Within the plasma sheath, ion density n_i and the electron density n_e can be described by:

$$n_\mathrm{i} = n_\mathrm{se}\left(\frac{\varphi_0}{\varphi}\right)^{\frac{1}{2}}, \tag{4}$$

$$n_\mathrm{e} = n_\mathrm{se}\exp\left(\frac{e(\varphi-\varphi_0)}{kT_\mathrm{e}}\right). \tag{5}$$

Poisson's equation is:

$$\frac{\mathrm{d}^2\varphi}{\mathrm{d}x^2} = -\frac{e}{\varepsilon_0}(n_\mathrm{i}-n_\mathrm{e}). \tag{6}$$

Substituting Eqs. (4) and (5) into Eq. (6), and integrating both sides by x after multiplying the both sides by $(\mathrm{d}\varphi/\mathrm{d}x)$, the following equation can be obtained:

$$\frac{\mathrm{d}\varphi}{\mathrm{d}x} = \left(\frac{2en_\mathrm{se}}{\varepsilon_0}\left(-2\varphi_0\left(\left(\frac{\varphi}{\varphi_0}\right)^{\frac{1}{2}}-1\right) + kT_\mathrm{e}\left(\exp\left(\frac{\varphi-\varphi_0}{kT_\mathrm{e}}\right)-1\right)\right)\right)^{\frac{1}{2}}. \tag{7}$$

The potential at the sheath edge, φ_0 and the floating potential on the pebble surface, φ_f are defined as below:

$$\varphi_0 = kT_\mathrm{e}, \tag{8}$$

$$\varphi_\mathrm{f} = kT_\mathrm{e}\ln\left(\left(2\pi\frac{m_\mathrm{e}}{m_\mathrm{i}}\right)\left(1+\frac{T_\mathrm{i}}{T_\mathrm{e}}\right)\right), \tag{9}$$

then, $E = \mathrm{d}\varphi/\mathrm{d}x$ on the pebble surface can be obtained by substituting Eqs. (8) and (9) into Eq. (7). The total charge of pebble surface Q_charge is given by:

$$Q_\mathrm{charge} = 4\pi\varepsilon_0 r^2 E. \tag{10}$$

The coulomb force, F_c, acting on the two pebbles, the gravity force, F_g, and the Lorentz force, F_L, are given by following equations:

$$F_\mathrm{c} = \frac{1}{4\pi\varepsilon_0}\frac{{Q_\mathrm{charge}}^2}{R^2}, \tag{11}$$

$$F_\mathrm{g} = \frac{4\pi r^3}{3}\rho_\mathrm{Sn}g, \tag{12}$$

$$F_\mathrm{L} = Q_\mathrm{charge}v_0B_\mathrm{e}. \tag{13}$$

These three forces are compared in Fig. 4. The Lorentz force is negligible compared with the gravity force, whereas the Coulomb force is larger than the gravity force if the center-to-center pebble distance is smaller than 14 mm. In such cases, the pebble flow will be rapidly spread by the Coulomb repulsion. Figure 5 shows the center-to-center pebble distance as a function of the drop distance at different injection velocities. If the molten tin pool is

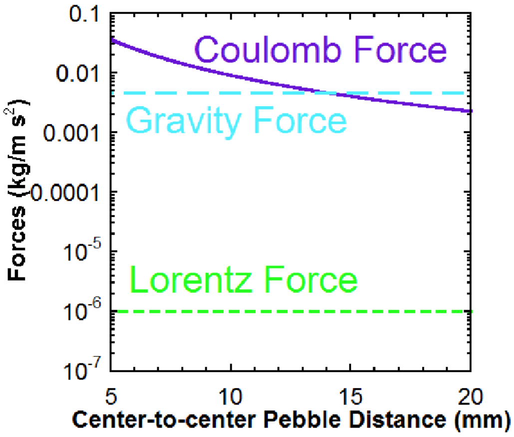

Fig. 4 The comparison of the gravity force, the Lorentz force, and the Coulomb force. The diameter of tin pebble is assumed to be 5 mm and the velocity of the tin pebble is 10 m/s.

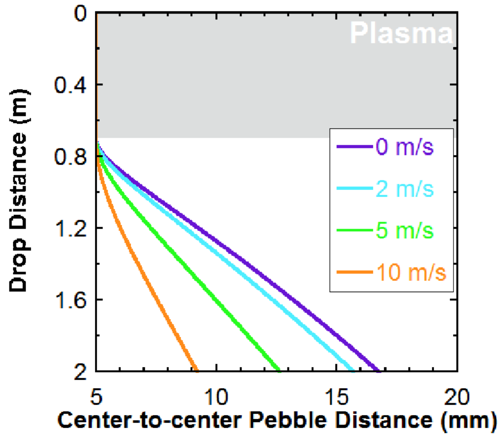

Fig. 5 The relation between the drop distance and the pebble distance. The tin pebble diameter of 5 mm and the injection velocity of 0, 2, 4, 10 m/s are assumed. The plasma hit the pebble in the hatched region of 0 - 0.7 m drop distance. The coulomb force does not act on pebbles in the plasma due to the sheath around the pebbles.

placed 2 m under the point where pebbles enter the ergodic layer, the radial displacement of the pebble is ~ 7 mm in the case of the injection velocity of 10 m/s. This level of the displacement can be accommodated by adjusting the shape of the receiver.

5. Summary

The fusible metal pebble divertor REVOLVER-D2 has been proposed, where showers of solid tin pebble flows are used as the divertor target, instead of the liquid tin shower jets in the former REVOLVER-D. The REVOLVER-D2 can realize simultaneous achievement of a high heat load capacity (~ 100 MW/m^2), a high evacuation efficiency, easy maintenance, together with mitigation of the MHD effect. No need of liquid metal pumps is also the merit. Charge up of the pebble can cause the Lorentz force and the Coulomb force. However, the Lorentz force is negligible if the injection velocity is fast enough. For example, the center-to-center pebble distance due to the Coulomb force will be ~ 4 mm in the case of the injection velocity of 10 m/s if the molten tin pool is placed 2 m under the point where pebbles enter the ergodic layer.

There are several issues which need to be investigated further. For instance, optimization of the pebble size is important because the pebble size strongly relates to the ratio of the Coulomb force to the gravity force, the heat removal capacity and the shielding rate. The condition of the silicone oil (e.g., viscosity, temperature) needs to be optimized according to the pebble size. The mechanical design of the pebble carrying part also needs to be considered.

Appendix

Constants and parameters used in this paper are listed in Tables 1 and 2.

Table 1 Physical properties of tin.

Symbol	Physical quantity	Value used in this paper (Solid)	(Liquid)
ρ_{Sn}	Density of tin (k/gm^3)	7,365	6,990
C_{Sn}	Specific heat (J/kg K)	226	243
χ_{Sn}	Heat of fusion (J/kg)	59,600	0
T_0	Initial temperature of the divertor target (K)	300	510

Table 2 List of parameters.

Symbol	Physical quantity	Value
Q	Volume flow rate	
ΔT_{all}	Average temperature of the tin pebble flow	
P_{div}	Divertor heat load	69.3 MW
P_{α}	α heating	74 MW
P_{aux}	Auxiliary heating power	25 MW
P_{rad}	Radiation loss	29.7 MW
P_{fusion}	Total fusion power	370 MW
ΔT_{pebble}	Average temperature of a pebble	
q	Heat load on the pebble shower	100 MW/m^2
Δt	Passing time of a pebble	
kT_e	Electron temperature	200 eV
kT_i	Ion temperature	60 eV
n_{se}	Plasma density at the sheath edge	1.2×10^{19}/m^3
r	Pebble radius	2.5 mm
B	Magnetic field	10 T
Q_{charge}	Charge on the pebble surface	
φ	Electric potential	
φ_f	Floating potential	
φ_0	Sheath potential	
m_e	Electron mass	9.1×10^{-31} kg
m_i	Ion mass	4.2×10^{-27} kg
e	Elementary charge	1.6×10^{-19} C
ε_0	Permittivity of vacuum	8.9×10^{-12} F m^{-1}
E	Electric field on the pebble surface	
R	Center-to-center pebble distance	

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